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# Improvement of instantaneous positioning by spatial stacking and modified sidereal filtering methods with application to the 2008 *M*s8.0 Wenchuan earthquake

Liu Gang, Li Gang, Tan Kai, Nie Zhaosheng, Zhou Yu and Jia Zhige
*Institute of Seismology, China Earthquake Adminstration, Wuhan* 430071, *China*

**Abstract**: We obtained several displacement time series from the Sichuan permanent GPS net and processed the 1-Hz data observed during a few days before the 2008 *M*s8.0 Wenchuan earthquake by double-difference instantaneous positioning technique. We filtered the data by the spatial stacking and the modified sidereal filtering methods to reduce correlation bias in space and time. The results indicate that these methods can improve the precision significantly.

**Key words**: 1-Hz GPS; spatial stacking; modified sidereal filtering; *M*s8.0 Wenchuan earthquake; deformation

## 1 Introduction

High sampling-rate GPS data may reveal rapid crustal deformation during an earthquake[1,2]. Combined with static GPS data they may provide strong constraints for inverting the earthquake-related slip distribution and history[3-5], thus making the application of high sampling-rate GPS data popular for studies in geodesy and seismology. Sichuan permanent GPS network has recorded a set of data showing large surface deformation caused by the 2008 *M*s8.0 Wenchuan earthquake at 1Hz, and this set of data had been processed with the double-difference instantaneous positioning method[6-9] by many researchers to study the co-seismic deformation. The double-difference instantaneous method is a relative-positioning technique, which calculates single epoch baseline and estimates deformation series with respect to a reference frame. It contains some errors, which can be reduced by applying the methods of spatial stacking and modified sidereal filter to the displacement series obtained by Bernese 5.0 software, as shown in this paper.

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First author: Liu Gang, Tel: +86-27-87863562; E-mail: whgpslg@gmail.com
Corresponding author: Tan Kai, E-mail: whgpstan@hotmail.com
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## 2 Data processing

### 2.1 Spatial stacking

Common-mode error is caused by global geodesy survey, such as orbital and reference-frame errors are similar for different sites within a certain spatial scope[10]. To reduce this kind of spatially-related errors in an area, the spatial stacking method may be used. In this method some remote sites where little earthquake-related displacement occurred are used as reference. The procedure is as follows:

1) Choosing some sites, where the displacements were hardly affected by the earthquake and had similar

spatially-related trends, as reference.

2) Applying box-car low-pass filtering (moving average filtering) to the displacement series of the reference sites to remove the high-frequency random noise unrelated to the satellite-receiver geometry.

3) Weighting and averaging the low-passed series of the reference sites to get the spatial stacking filter as follows

$$v = \sum_{i=1}^{n} (W_i \cdot V_i) \Big/ \sum_{i=1}^{n} W_i \tag{1}$$

where $n$ is the number of reference sites, and $V_i$ and $W_i$ are, respectively, the displacement and the weight of the $i$th reference site.

4) Subtracting the common error from the original displacement time series of the other sites with the filter.

### 2.2 Modified sidereal filtering

Multipath error, such as signal attenuation and diffraction or recycle movement of observation pillars or other variations which have the same cycle as GPS-orbit repeat period, is a systematic noise introduced by GPS orbits and the environment of the receivers[11]. These errors can be averaged out and highly reduced by estimating daily solutions, using many epochs. However, for single epoch solution, the multipath error is a significant nuisance term severely reducing positioning precision because it cannot be reduced by averaging. Sidereal filtering is a temporal filtering method, which eliminate multipath error by filtering the time series of a single site within contiguous orbital cycles. Theoretically GPS orbits have a cycle of a sidereal day (23 h 56 min 4 s), but later K. Choi, et al. found that the cycle was not so precise but varying[12]. Modified sidereal filtering regards the mean orbital cycle instead of the sidereal day as the cycle in studying multipath error. Therefore, this method is based on the similarity multipath error for single site within contiguous orbital cycles. The procedure is as follows:

1) Calculating GPS orbit average cycle with the following formula and regarding it as the cycle of the filter.

$$\bar{T} = \frac{\sum_{i=1}^{n} 2\pi a^{2/3} \mu^{-1/2}}{n} \tag{2}$$

where $n$ is the number of satellites observed, $a$ is the semi-major axis, $u$ is GM-gravitational constant, which can be read from the head of navigation file.

2) Removing high frequency random noise by filtering linear series without earthquake within contiguous orbital cycles by applying a box-car filter.

3) Weighting and averaging multi-orbital-cycle linear series without earthquake to get the filter by formula (1), where $n$ is the number of cycle linear series. $W_i$ is the weight of the $i$th series, $V_i$ is the $i$th cycle linear series.

4) Subtracting the linear-change term by applying the filter to the orbital series which contains nonlinear change caused by earthquake.

## 3 Displacement analysis

The 2008 $Ms8.0$ Wenchuan earthquake caused large surface deformation. The Sichuan GPS network recorded pre-seismic data at a rate of 1-Hz as usual, but the co-seismic data for only 67 second, because of the recording disruption. By using the double-difference instantaneous positioning method and WUH2 site as reference frame, we processed the GPS data of PIXI, CHDU, ZHJI, MYAN, YAAN and LUZH sites (Fig. 1), for two days (130 day and 131 day) before the earthquake and the day (133 day) of the earthquake. For each day we processed the data for one hour, which is 3600 epochs by using Bernese5.0. The horizontal formal error is within 1 cm for all these sites. To assess the scatter of the series before and after the filtering, we calculated the *RMS* values by using the following formula:

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{X})^2}{n}}$$

where $x_i$ is the deformation of each epoch, $\bar{X}$ is the mean deformation, and $n$ is the number of the epoch before the earthquake.

### 3.1 Result of Spatial Stacking

The use of double-difference instantaneous positioning technique without spatial stacking showed a mean RMS of 50 mm for the displacement time series of the 6 sites for the one-hour period before the earthquake. The EW components of the time series are show in figure 2(a), where the sudden drops were caused by the earthquake. The similarity in fluctuation in the series between different sites, which are so far apart, indicates a high spatial correlation, and thus the existence of a common error, which can be reduced by spatial stacking.

Because of the relatively long distance between epicenter and the sites YAAN and LUZH, we choose them as reference sites for the spatial stacking filtering. To subtract high frequency random noise, we applied a box-car (7 s) low-pass filter to the series of YAAN and LUZH. According to Formula (1), the low-pass filtered series were averaged with the same weight and may be used as a filter for the other four sites. The filter is shown in figure 2(b).

The results after spatial stacking filtering are shown in figure 3(a). It my be seen that the linear common error has been reduced, rendering the nonlinear component clearer. A zoom-in view of the time series during the earthquake is present in figure 3(b). As a measure of scattering in the time series, the mean RMS values for these 4 sites are reduced to 25 mm (for PIXI, to 49 mm).

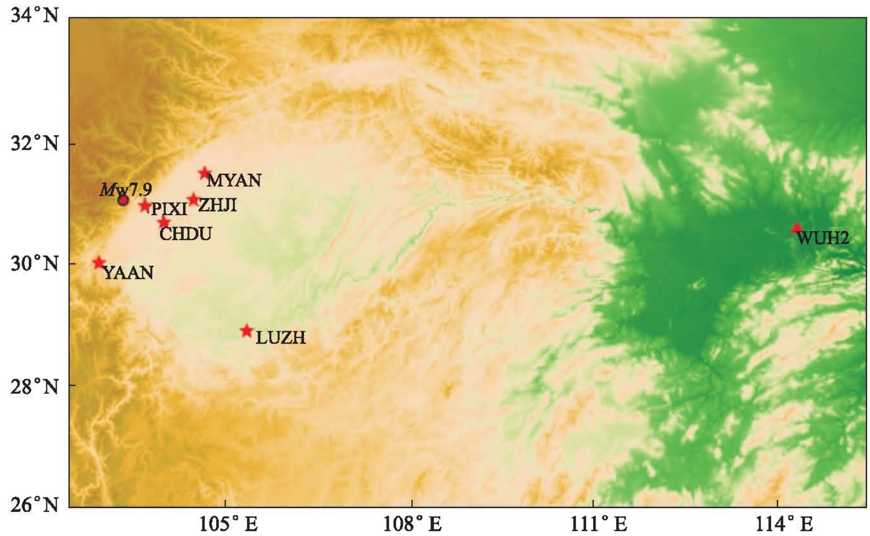
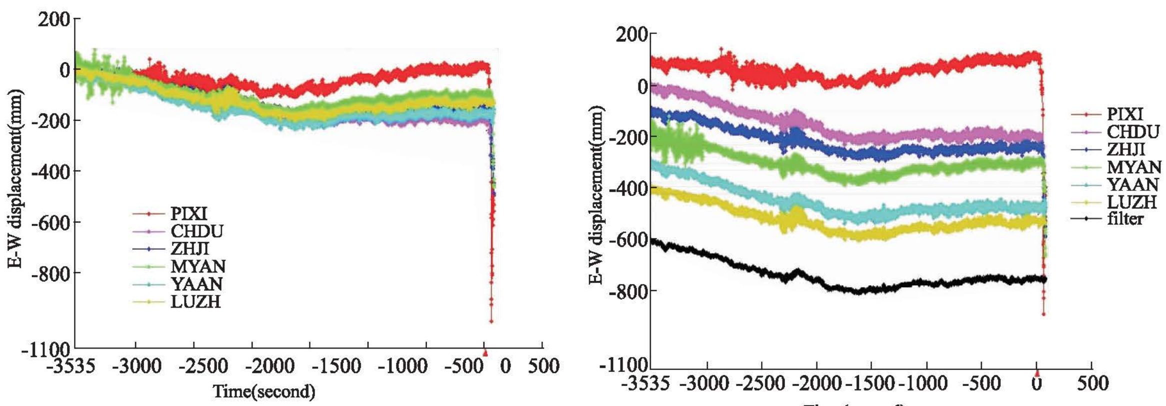



Figure 1 Location of 6 GPS sites (red stars) and reference frame site WUH2 (red triangle). Red circle indicates the epicenter of Wenchuan *M*s8.0 earthquake




(a) EW-displacement time series of 6 GPS sites during one-hour period before and during the earthquake (indicated by red triangle)

(b) Spatial correlation and the filter of spatial stacking

Figure 2 Spatial correlation presented from time series of the 6 GPS sites

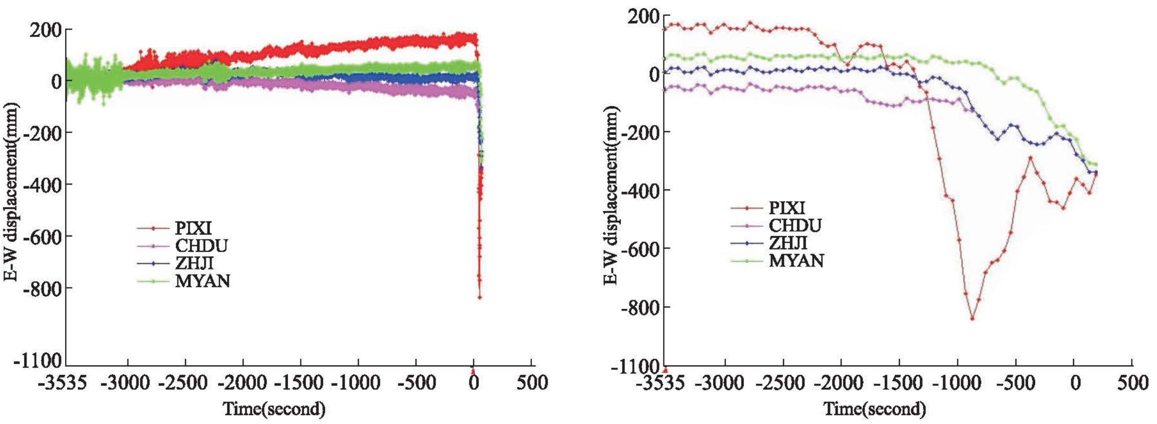
### 3.2 Result of modified sidereal filtering

Figure 4 (a) shows unfiltered EW displacement timeseries for PIXI site, on days 130, 131 and 133 (day of earthquake occurrence), showing a similar and significant linear term with a mean RMS value of 68 mm. The linear component of PIXI site has the same cycle as the GPS orbits. Since other errors have been subtracted during the double-difference instantaneous positioning process, the orbital-repeat-correlated error, which has an orbital cycle, may be considered as a multi-path error and thus can be reduced by modified sidereal filtering.

We obtained a mean orbital cycle of 23 hour 5 minute 58 second, which was regarded as the cycle for multi-path error. We got modified sidereal filter by applying box-car filtering and the same weighting to the time series in the same cycle of 130 day and 131 day with respect to 133 day, and then modify the time series of 133 day with the filter. Figure 4(b) shows the time series modified by the sidereal filtering on 133 day, which is smoother, clearer, and less varied than before. By reducing the orbital-repeat-correlated error, the RMS value for the time series is reduced to 45 mm.

### 3.3 Combined filtering

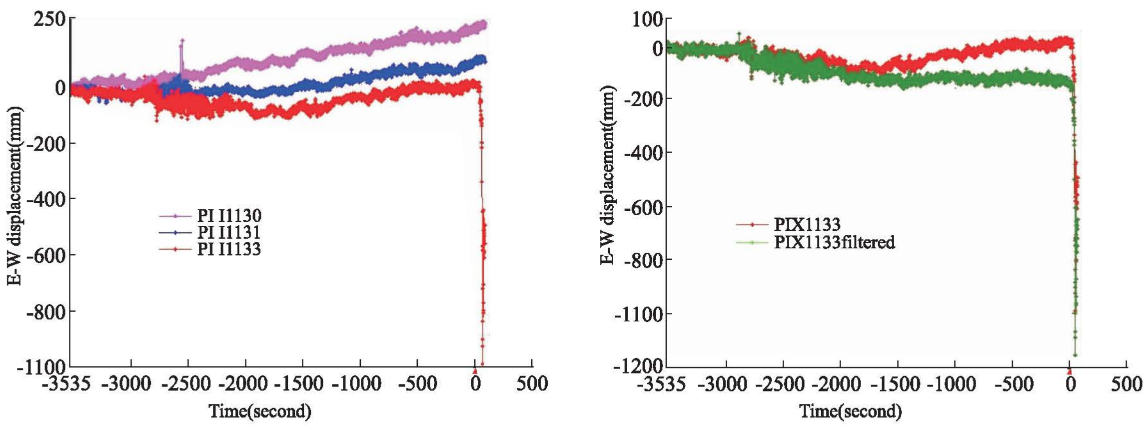
Both spatial stacking and modified sidereal filtering have clarified the time series of 133 day, on which the earthquake occurred. However, each of these results (Figs. 3(a) and 4(b)) still contains significant linear component when these methods were applied separately.




(a) The EW-displacement time series of 4 sites filtered by space stacking

(b) A zoom-in view of the series during the last minute

Figure 3 The displacement time series filtered by space stacking



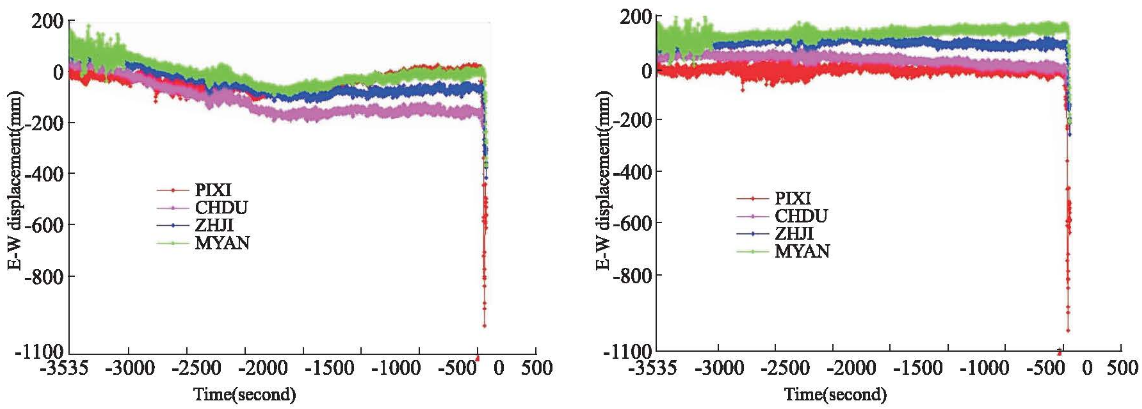

(a) EW displacement time series of PIXI site during the 130, 131 day prior to the earthquake and 133 day of earthquake occurrence, showing multi-path error

(b) Comparison of EW displacement time series of PIXI during the one-day orbital cycle before and of the earthquake with and without filtering by the modified sidereal method

Figure 4 Multipath error of PIXI and modified sidereal filtering

We found that the multi-path error with a quasi-sidereal cycle was usually linked with some spatially related common-mode error. The repeated multi-path error and the daily spatial common-mode error may co-exist on different days in the time series, and the common-mode error may also have a quasi-sidereal cycle (Figs. 2(a) and 4(a)).

We also found that the result calculated by modified sidereal filtering (Fig. 4(b)) is better than that calculated by spatial stacking (Fig. 3(a)) for PIXI site. Since the modified sidereal filtering reduces multipath error by differencing nonlinear series containing earthquake with average weight of the multi-orbital-cycle linear series in which multi-path error and common-mode error co-exist, it also reduce the common-mode error to some extent. In order to reduce both of these errors, we developed a combined filtering, by first applying the modified sidereal filtering and, if the spatially correlated error still exists, then the spatial stacking filtering. We applied the combined method to PIXI site and the other 3 sites, and found that both the linear temporal error and the spatially correlated error were effectively eliminated (Fig. 5). The mean RMS values in the time series were greatly reduced to 16 mm for the four sites, and 15 mm for PIXI.




(a) EW-displacement time series of 4 GPS sites before and during the earthquake

(b) The same time series after combined filtering

Figure5 Time series before and after combined filtering

## 4 Conclusions

We applied spatial stacking method and modified sidereal filtering to the displacement time series recorded a few days before the Wenchuan earthquake, and found that they, respectively, reduced the spatially correlated common-mode error and the GPS orbit-repeat-correlated multipath error, and thus improved the precision of instantaneous positioning. We also found that by combining these methods we may get a even better result.

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## References

[1] Bock Y, et al. Instantaneous geodetic positioning at medium distances with the Global Positioning System. J Geophys Res., 2000, 105(B12), 28223 – 28253.

[2] Kristine M, et al. Using 1-HZ GPS data to measure deformations caused by the Denali fault earthquake. Science, 2003, 300: 1421 – 1424.

[3] Tan Kai, et al. Lithospheric rheological structure constrained by geodetic data in Altay. Chinese J. Geophys, 2007, 50(6): 1713 – 1718. (in Chinese)

[4] Chen Ji, et al. Slip history of the 2003 Simeon earthquake constrained by combining 1-Hz GPS, strong motion and teleseismic data. Geophysical Research Letters, 2004, 31, L17608, doi: 10.1029/2004GL020448.

[5] Yusuke Yokota, et al. Ability of 1-HZ GPS to infer the source process of a medium-sized earthquake: the 2008 Iwate-Miyagi Nairiku, Japan, earthquake. Geophysical Research Letters, 2009, 36(L12301).

[6] Xiong Yongliang, et al. Long distance kinematic GPS data pro-

cessing and Kinematic crustal deformation features analysis of Wenchuan earthquake. Geomatics and Information Science of Wuhan University, 2009, 34(3):265 -269. (in Chinese)

[7] Xu Shaoguang, et al. Static and Kinemaic Analysis of Co-seismic Deformation of Wenchuan 8.0 Earthquake. Journal of Geodesy and Geodynamics, 2010, 30(3): 27 -30,54. (in Chinese)

[8] Yin Haitao, et al. Near-field surface movement during the Wenchuan *Ms*8.0 earthquake measured by high-rate GPS. Chinese Sci Bull, 2010, 55(26), 2621 -2626. (in Chinese)

[9] Using ultra long baseline to measure co-seismic kinematic deformations of Wenchuan earthquake. Journal of Geodesy and Geodynamics, 2011, 31(5): 14 -19. (in Chinese)

[10] Shimon Wdowinski, et al. Southern California permanent GPS geodetic array: Spatial filtering of daily positions for estimating co-seismic and post-seismic displacements. J Geophys Res., 1997, 105(B12):18057 -18070.

[11] Fang Rongxin, et al. Precise Point Positioning with High-rate GPS Data Applied to Seismic Displacements Analysis. Geomatics and Information Science of Wuhan University, 2009, 34(11), 1340 -1343. (in Chinese)

[12] Choi K, Bliich A, Larson K M, et al. Modified sidereal filtering: Implications for high-rate GPS positioning. Geophys Res Lett, 2004, (31), L22608, doi:10.1029/2004GL021621.